Accounting for Capital Consumption and Technological Progress

by Michael Gort and Peter Rupert

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Introduction

Oscar Wilde defined a cynic as a person "who knows the price of everything and the value of nothing," and a sentimentalist as one "who sees an absurd value in everything but doesn't know the market price of any single thing." Most economists would probably object to the first definition, for to know the price of something is to know what value society (that is, the market) places on the last unit. And while few people regard the Internal Revenue Service as sentimental, it has, at least implicitly, adopted the practice of placing values on capital goods, usually without knowing their prices.

Computing the value of the stock of capital, especially in the face of technological advance, is a large task, complicated by the fact that assets may lose value over time because of physical wear and tear as well as obsolescence. When calculating income, owners of capital are allowed to deduct from earnings the amount of capital that is consumed by the production process (depreciation), termed *capital consumption* in the National Income and Product Accounts (NIPA). Deriving a measure of the aggregate capital stock entails adding up assets that have very different lives, hence very different depreciation patterns.

Difficult as it may be, obtaining fairly precise estimates of the capital stock is important. One area where reliable estimates are necessary is that of growth accounting. As its name suggests, its goal is to determine the underlying sources of economic growth in order to account for the growth in output. How do we create more and more output over time? At a very simple level, the inputs that produce the output might be increasing, or technological advance in the economy might give us more from the same expenditure on inputs.

At a slightly deeper level, suppose that the only two inputs are physical capital (computers, trucks, and so forth) and labor. Output is derived from these two inputs through some production process. Now suppose that output is observed to be growing over time. If there are no measurement problems, it is possible to determine what underlies growth in the economy. Observed growth, for example, might be attributed to growth in the labor force, more computers, or both. Simple enough.

To complicate things a bit more, suppose that output is observed to be growing faster than the measured growth in inputs. Now what? It is possible that there is an input not included in the simple, two-factor (capital and labor) model. For example, there might be a change in how labor and capital are combined, as when new business practices enable better communication. Obviously, this could be difficult to measure with any accuracy. Such unmeasured influences go into a catchall component called *total factor productivity*.

But there is another explanation for the gap between input growth and output growth. Suppose inputs are not measured correctly due, for example, to technological growth in one or both of them. Imagine that given some labor input, the capital stock (say computers) is increased. The complication would arise if the new computer were twice as fast as the old one and, therefore, able to produce much more. If that feature were not taken into account, the new computer would be added as if it were an old one, and growth in the capital stock would be mismeasured. Hence, too little of the economy's growth would be attributed to capital's contribution and too much to total factor productivity. Such technological growth in capital is known as *capital-embodied* technological change.

The same could be true of labor, giving rise to *labor-embodied* technological advance. Understanding where growth comes from has important implications for policy making. With accurate measurement, policies can be designed to devote resources to the most productive uses. For example, it would be possible to assess the contribution to growth of spending an additional $1 billion on education programs, thus increasing the level of human capital. Or to gauge the impact of spending that sum to promote research and development in the computer industry.

To obtain an accurate measure of capital, it is important to know not only how productive a new vintage of capital is, but also how quickly the old capital loses value. Obviously, the faster an asset is used up in the production process, the higher the investment rate needed to keep the stock of capital constant. But assets may also become obsolete (that is, used up) in a different sense. A computer loses value over time because newer models are so much better per dollar spent, not because its keyboard doesn't work properly or its hard drive is leaking oil. The amount of capital consumption the Internal Revenue Service allows will have a substantial impact on the rate of investment in the economy. In fact, the depreciation allowance has been used to increase investment in specific industries. Pollution control facilities, rehabilitation of low-income housing, the railroad rolling stock, and coal-mining safety equipment are instances of such specific targeting. In addition, depreciation has been used as a countercyclical policy instrument. For example, when the economy began to overheat in 1966, the investment tax credit implemented in 1962 to spur investment was suspended, as were accelerated depreciation methods for real property. By the end of 1967, the economy had begun to weaken and those policies were reinstated.[1]

I. Aggregating and Measuring a Heterogeneous Capital Stock

A two-step procedure is conventionally used to measure capital consumption, whether for depreciation of individual firms or for aggregate estimates tied into the NIPA. First, the asset's useful economic life is estimated (based mainly on estimates of the Internal Revenue Service). Second, the asset's original cost is allocated over the estimated useful life to measure each year's capital consumption (depreciation). To compute the aggregate stock of capital in the NIPA, each year's investment is deflated by a price index, and depreciation for it is computed separately. By aggregating current capital consumption charges from all past investments, each year's estimate of aggregate capital consumption in real terms is obtained. And by aggregating the net deflated investments from previous years (net of all current and past capital consumption charges) a so-called "perpetual inventory" capital stock is derived for each year in the NIPA.

This approach has several problems. First, the estimates of useful life are of undetermined reliability. Second, methods of allocating original cost to derive capital consumption, the most common being "straight line" and "declining balance," are quite arbitrary.[2] Third, with only a few exceptions, price indexes used for deflation do not take account of changes in the quality of capital over time. Thus, the resulting investment streams, when aggregated over time, are not expressed in homogeneous efficiency units. Fourth, depreciation or capital consumption lumps together obsolescence and physical decay, making it impossible to identify the separate effects of technological change—as opposed to wear and tear on the net stock of capital.

1 See Brazell, Dworin, and Walsh (1989) for a more in-depth discussion.

2 The past several years have seen efforts to obtain better estimates of both useful lives and depreciation patterns. See *Survey of Current Business* (1998).

Gort, Greenwood, and Rupert (1999) seek to surmount all these problems in their estimates of obsolescence and physical decay for structures. Focusing on office buildings and using data provided by the Building Owners and Managers Association, they estimate 1) the rate of obsolescence over the life of a building; 2) the rate of physical decay as a building ages; and 3) the implications of these estimates for economywide growth in capital and for the contribution to economic growth of the underlying measured inputs: equipment, structures, and labor. The authors also derive the contribution of disembodied technological progress (total factor productivity).[3]

Contrary to the common assumptions that technological progress is limited to equipment and that a building's life span is largely defined by its rate of physical decay, the authors find a substantial rate of technological advance. Such advance explains a significant fraction of economywide capital growth and changes the share attributed to total factor productivity.

These estimates are made possible by data based on market prices. Specifically, a relation is established between a building's age on the one hand and both the total rental revenue and the gross operating profit generated from rentals on the other. The authors estimate the net effects of a building's age (or vintage) on (a) the rental revenue per square foot and (b) the gross operating profit per square foot. After allowing for the effects of several other variables such as the building's location, variable (a) gives the effect of vintage on the decline in the gross flow of productive services as the building ages, and (b) gives the effect of vintage on the decline in income that the building generates.

The key idea is that a new building should rent for more because it embodies more advanced technology. Here, rent's rate of decline measures the technological advance of structures in the economy. In addition, it will be more profitable for a newer building to employ equipment and labor that uses a more recent technology.

Decoupling obsolescence from physical wear and tear is a formidable task because economic depreciation is defined as the rate at which an asset loses value over time.[4] Both obsolescence and physical wear and tear contribute to the decline in asset value; moreover, different types of assets will exhibit different patterns of decay attributable to those underlying components. For example, the useful service life of the computer used to type this article is quite short (about three years). Evidently, nearly all of computers' age-related decline in value results from technological advance. Each year, computers become much faster, have more memory and storage, and so on, but virtually no loss due to physical wear and tear. In other words, the three-year-old computer produces almost exactly the same amount of output as when it was brand new, but it has lost value because it is vastly inferior to a new model. Automobiles differ from computers in that while there certainly are technological improvements (such as ABS brakes, air bags, and so on), physical wear and tear play a much larger role. Many of a car's internal parts must be replaced or repaired long before it loses all of its value.

Gort, Greenwood, and Rupert (1999) infer that the decline in revenue results from technological change, that is, obsolescence. This conclusion is based on the fact that building owners must maintain, both by rental contract and by local ordinances, the safe and effective use of the building through appropriate repair and maintenance outlays. Office buildings cannot be used if they have water leaks, have nonfunctioning heating and plumbing systems, unsafe elevators, loose bricks, and so on. Repair and maintenance costs therefore must cover this physical decay, at least insofar as it affects the safe, effective use of office space. These expenditures can be viewed as investments to cover and inhibit physical depreciation. And, as shown below, repair and maintenance costs rise systematically as a building ages. Over time, they cut into a building's revenue and therefore influence its useful service life. It should be stressed that the implied definition of obsolescence is a very broad one, which captures all sources of decline associated with economic progress, including architectural changes that allow better use of space, light, and so on.

Engineering advances enable the occupants of a building to work in greater comfort. For example, anti-sway devices, located in the tops of skyscrapers, limit the extent of the buildings' movement. "Sky lobbies" permit an elevator car to move into an alcove when admitting or discharging passengers, allowing the next car to pass. Advances in other areas, such as the introduction of computers, can also lead to a form of obsolescence, since the need for routing new fiber-optic cables to set up networks

■ **3** Total factor productivity can be thought of as a factor that scales up the value of all inputs to equal the output. For example, if inputs of all factors of production equal \$5 and produced output that is sold at \$10, then total factor productivity would equal 2.

■ **4** In statistical or econometric terms, the problem is one of identification. See Hall (1968) or Hulten and Wykoff (1981).

requires that a building's interior be amenable to such changes.

Gort, Greenwood, and Rupert (1999) incorporate existing data into a theoretically based economic model that uses these data to impose discipline on the behavior of the model itself. These and other building-specific data were obtained from analyses performed by the Building Owners and Managers Association International, which has been collecting data on individual office buildings across the United States and Canada for over 70 years. The collected data include information on size, expenditures for repair and maintenance, region, occupancy rates, and, most importantly for this exercise, rent.[5]

Two important facts emerge from the data. First, rent per square foot declines with the age of the building.[6] Second, repair and maintenance costs increase.[7]

The results from regression analyses show that after adjusting for inflation, rent per square foot declines about 1.5 percent annually, and repair and maintenance costs rise about 2 percent annually.

Because rents are declining with age while maintenance costs are increasing, a building will eventually cease to be profitable and will be razed to make room for a newer, more productive one. That is, it will be replaced by a structure with the latest advances in technology, such as faster elevators, better heating, ventilation, air conditioning, and safety equipment, adjustable interior space, and so on.

With the estimates and restrictions placed on it, the model shows that the growth rate of technology in office buildings has been about 1 percent annually. That, in conjunction with the fact that technological progress in equipment (by one estimate) has been about 3.2 percent annually,[8] allows U.S. output growth from capital accumulation to be broken down into its underlying components.[9]

Specifically, structures are found to account for approximately 15 percent of economic growth, and equipment for approximately 37 percent. The remaining 48 percent is attributed to labor inputs and total factor productivity; that is, it cannot be attributed to any specific factor.

The model also allows an exact measurement of the capital stock. Note that in the presence of technological change, aggregating across different vintages becomes a daunting task, because one must know how much better each successive generation of capital is. Further, the embodiment of technological change in capital means that changes in each generation must be converted into a common unit to make aggregation across different vintages possible. However, results from the model of the pace of technological growth make it possible to determine the exact number of efficiency units of capital. For example, the NIPA show that the growth rate of nonresidential structures per person-hour between 1959 and 1996 has been 0.75 percent annually.

Results from the Gort, Greenwood, and Rupert model suggest that this growth rate is 2.4 percent annually, a substantial difference. Likewise, the NIPA estimate of the growth rate in the stock of equipment is 2.5 percent annually, while the model puts it closer to 4.4 percent annually. This suggests that the NIPA substantially underestimates the size of the capital stock, once one takes into account technological advances embedded in new capital are taken into account.

II. Conclusion

Current methods used to calculate capital consumption, the stock of capital, and the sources of growth in the economy do not adequately measure the underlying growth in inputs due to technological advance. This has implications for tax policy as well as the design of programs targeting specific areas that can lead to higher growth in the economy.

■ **5** Since the data are proprietary in nature, the Association provided them without exact building identifiers. The data used in Gort, Greenwood, and Rupert (1999) were based on the years 1988–96.

■ **6** This result is based on a regression in which the dependent variable is the log of real rent per square foot and the independent variables are age, region of the country, calendar year, and a constant term.

■ **7** A similar regression was used to determine the exact rate of increase in repair and maintenance costs with age.

■ **8** Taken from Greenwood, Hercowitz, and Krusell (1997) and based on prices from Gordon (1990).

■ **9** This is based on the assumption that other types of nonresidential structures have seen the same rate of technological progress.

Appendix

This technical appendix provides the underlying mathematical framework of the model, although it leaves out many details, such as the parameters used in the calibration. The reader is referred to Gort, Greenwood, and Rupert (1999) for those missing details.

Production is undertaken at a fixed number of locations, distributed uniformly on the unit interval, and requires the use of three inputs: equipment, structures, and labor. Each location is associated with a stock of structures of a certain age or vintage. Equipment and labor can be hired each period on a spot market. Let production at a location using structures of vintage j be given by

$$\text{(A1)} \qquad o(j) = zk_e(j)^{\alpha_e}k_s(j)^{\alpha_s}l(j)^{\beta},$$

where z is the economywide level of total factor productivity, and $k_e(j)$, $k_s(j)$, and $l(j)$ are the inputs of equipment, structures, and labor. Denote the number of locations using structures of vintage j by $n(j)$, and let the maximum age of structures be T. Then $\int_0^T n(j)dj = 1$. Aggregate output is thus

$$\text{(A2)} \qquad y = \int_0^T n(j)zk_e(j)^{\alpha_e}k_s(j)^{\alpha_s}l(j)^{\beta}dj.$$

Output can be used for four purposes: consumption, c, investment in new equipment, i_e, investment in new structures, i_s, and investment in repair and maintenance on old structures, i_m. Hence,

$$\text{(A3)} \qquad c + i_e + i_s + i_m = y.$$

Imagine constructing a new building at some location. Suppose that a unit of forgone consumption can purchase v new units of structures. Then, building $k_s(0)$ units of new structures would cost $k_s(0)/v$ units of consumption. Let v grow at the fixed rate γ_v; this denotes structure-specific technological progress.[10] Structures remain standing until they are replaced. Expenditures on repair and maintenance keep buildings in their original condition. Those costs grow over time, $\mu(j) = e^{(\gamma_\mu + \gamma_y)j}$.

The static profit-maximizing decision at a location using structures of vintage j is represented by

$$\text{(A4)} \qquad \pi(j) = \max_{k_e(j),l(j)} \begin{Bmatrix} zk_e(j)^{\alpha_e}k_s(j)^{\alpha_s}l(j)^{\beta} \\ - r_ek_e(j) - wl(j), \end{Bmatrix},$$

where r_e is the economywide rental price for equipment and w is the wage rate. The manager's date-0 problem can be written as the following value function:

$$\text{(A5)} \qquad V[k_{s,0}(0)] = \max_{k_{s,T}(0),T} \left\{ \int_0^T [\pi_t(t) - \mu(t)k_{s,0}(0)/v_0]e^{-\iota t}dt + e^{-\iota t}[V(k_{s,0}(0)) - k_{s,T}(0)/v_T] \right\},$$

where ι represents the time-invariant interest rate, and the initial maintenance cost is a fraction $\mu(0)$ of the building's purchase price. As the building ages, these costs grow exogenously at rate $\gamma_\mu + \gamma_y$, where γ_y is the economy's growth rate.

At each point in time, the equipment manager has k_e units of equipment that he can rent out at r_e. He must decide how much to invest, ι_e, in new equipment. This investment can be financed at the fixed interest rate ι. The optimal control problem governing the accumulation of equipment is summarized by the current-value Hamiltonian:

$$H = r_ek_e - i_e + \lambda[i_eq - \delta_e k_e].$$

Let a consumer's lifetime utility function be given by

$$\int_0^\infty \ln c_t e^{-pt}dt.$$

Now, the consumer is free to lend in terms of bonds, a, earning the return ι. In addition to the interest he realizes on his lending activity, w, and the profits from his locations (net of any repair and maintenance costs and investment in structures). The law of motion governing his asset accumulation reads

$$da/dt = \begin{aligned} & w + \iota a + \int_0^T n(j)[\pi(j) \\ & - \mu(j)k_s(j)e^{\gamma_v j}/v]dj - n(0)k_s(0)/v - c. \end{aligned}$$

The balanced growth path can be uncovered using a guess-and-verify procedure.

Now, consider the economy's cross-section of buildings at a point in time. It is easy to calculate that the percentage change in rents as a

10 The focus of the analysis is on balanced growth paths. As a result, some variables, such as aggregate output, will grow over time at constant rates; others, such as the interest rate, will be constant.

function of age (the rent gradient δ_s) should be given by

$$\text{(A6)} \quad \delta_s = \frac{\alpha_s}{1 - \alpha_e - \beta} \gamma_s,$$

since the stock of structures declines at rate γ_s as a function of age, while factor prices remain constant. This formula gives a measure of obsolescence in buildings. In the absence of depreciation, a new building rents for more than an old one only because it offers more efficiency units of structures.

The model can then be calibrated using such information as the rate of decline in rents for buildings, the average annual growth rate of output, and so on, to obtain the underlying sources' contribution to growth.

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